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Microarticle

Extended Chaplygin gas model

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ABSTRACT

In this note we would like to introduce extended Chaplygin gas model as alternative to the dark energy. Advantage of this model relative to the previous versions is that recovers barotropic fluid with quadratic and higher order equation of state.

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An interesting model of dark energy is based on Chaplygin gas equation of state [1]. In order to have more agreement with observational data it was extended to the generalized Chaplygin gas [2] including the possibility of viscosity in GCG [3]. Then, GCG was extended to the modified Chaplygin gas [4]. A further extension of CG model is called modified cosmic Chaplygin gas (MCCG) which was proposed recently [5]. The MCG equation of state (EoS) has two parts, the first term gives an ordinary fluid obeying a linear barotropic EoS, and the second term relates pressure to some power of the inverse of energy density. However, it is possible to consider barotropic fluid with quadratic EoS or even with a higher order EoS [6]. Therefore, it is interesting to extend MCG EoS which recovers at least barotropic fluid with quadratic EoS. Modified Chaplygin gas was introduced with the following equation of state,

$$p = A\rho - \frac{B}{\rho^{\alpha}}, \tag{1}$$

where $0 < A < 1/3, 0 < \alpha < 1$, and B is a positive constant. The case of $A = 0$ recovers generalized Chaplygin gas EoS, and $A = 0$ together $\alpha = 1$ recovers the original Chaplygin gas EoS. Moreover, the first term on the r.h.s. of the Eq. (1) gives an ordinary fluid obeying a barotropic EoS, while there are other barotropic fluids with EoS being quadratic and higher orders. Since modified Chaplygin gas can only recover linear form of barotropic EoS, here we would like to extend this model so that resulting EoS can also recover EoS of barotropic fluids with higher orders. In that case we propose the following EoS,

$$p = \sum_{i=1}^{n} A_i \rho^i - \frac{B}{\rho^{\alpha}}, \tag{2}$$

which is called extended Chaplygin gas EoS. It reduces to MCG EoS for $n = 1$, and can recover barotropic fluid with quadratic EoS by setting $n = 2$. Also, higher n may recover higher order barotropic fluid which is indeed our motivation to suggest extended Chaplygin gas. Before discussing the model in general, we represent a special case of fixed B and $A = \frac{1-\alpha}{1+\alpha}$ to investigate time-dependent scale factor by variation of α. Under such assumption we get from the Eq. (2) that as a increases $(0 < \alpha < 1)$, the first term on the r.h.s. reduces to zero while the second term decreases for a chosen energy density. Now, we would like to consider a general case and give numerical analysis of the cosmological parameters such as scale factor, dark energy density and Hubble expansion parameter with an arbitrary choice of n and α. Before doing this, we obtain an expression for the energy density corresponding to $\alpha = 0.5$. After some calculations we can find,

$$\rho = \frac{\left(\mathcal{C} a^{\frac{9}{2}} + a^{-\frac{9+\sum_n 6(n-1)\mathcal{C}^{2(n-1)}}{2}A}\right)^2}{a^9}, \tag{3}$$

where $\mathcal{C}$ is the root of $A\sum_n \mathcal{C}^{2n+1} + (1+A)\mathcal{C}^3 - B = 0$. Numerically, we can obtain behavior of scale factor against t. We can find that increasing n decreases the value of the scale factor. It is easy to show that increasing n decreases the value of energy density. As expected, energy density obtained here is a decreasing function of time which yields an infinitesimal constant at the late times. We find that evolution of scale factor corresponding to $n = 1$ (linear barotropic fluid) is faster than the case with $n = 2$ (quadratic barotropic fluid). We also find that Hubble expansion parameter and

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dark energy density are decreasing with n. We analyze $H(z)$ and compare our results with observational data. We found that, by choosing appropriate values of constant parameters, our model has more agreement with observational data than ΛCDM. We study density perturbations,

$$\ddot{\delta} + H[2 - 3(2\omega - C_s^2)]\dot{\delta} - \frac{3}{2}H^2(1 - 6C_s^2 - 3\omega^2 + 8\omega)\delta = -k^2\frac{C_s^2}{a^2}\delta, \tag{4}$$

where δ is the density fluctuation, k is the wavenumber of the Fourier mode of the perturbation, $\omega = p/\rho$, and $C_s^2 = \dot{p}/\dot{\rho}$ is squared sound speed. Therefore, we are able to investigate the stability of our model using the behavior of δ and $C_s^2 \geqslant 0$ condition. We focus on special case of $n = 1$ (MCG), $n = 2$ and $n = 3$. We find that the cases of $n = 2$ and $n = 3$ are completely stable because perturbations vanish and squared sound speed is positive. Therefore, we concluded that ECG may be a more appropriate model than MCG and GCG and is in agreement with the observational data. In summary, the case of $n = 2$ has a good agreement with observational data, hence we propose the following EoS for Chaplygin gas models,

$$p = A_1\rho + A_2\rho^2 - \frac{B}{\rho^\alpha}. \tag{5}$$

It yields a good behavior for cosmological parameters such as Hubble, deceleration and EoS parameters. It is also possible to construct inflationary and bouncing solutions which are subjects of our current works. Therefore, it may be used as unified history of universe.

However one can perform more investigations about higher n and include further terms, in that case we think that the effects of correction terms will be infinitesimal and have few importance at the early universe, and vanish at the late time.

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